

# Orion MPCV GN&C End-to-End Phasing Tests

Brian C. Neumann<sup>1</sup>

*Jacobs Technology, Houston, TX, 77058*

End-to-end integration tests are critical risk reduction efforts for any complex vehicle. Phasing tests are an end-to-end integrated test that validates system directional phasing (polarity) from sensor measurement through software algorithms to end effector response. Phasing tests are typically performed on a fully integrated and assembled flight vehicle where sensors are stimulated by moving the vehicle and the effectors are observed for proper polarity. Orion Multi-Purpose Crew Vehicle (MPCV) Pad Abort 1 (PA-1) Phasing Test was conducted from inertial measurement to Launch Abort System (LAS). Orion Exploration Flight Test 1 (EFT-1) has two end-to-end phasing tests planned. The first test from inertial measurement to Crew Module (CM) reaction control system thrusters uses navigation and flight control system software algorithms to process commands. The second test from inertial measurement to CM S-Band Phased Array Antenna (PAA) uses navigation and communication system software algorithms to process commands. Future Orion flights include Ascent Abort Flight Test 2 (AA-2) and Exploration Mission 1 (EM-1). These flights will include additional or updated sensors, software algorithms and effectors. This paper will explore the implementation of end-to-end phasing tests on a flight vehicle which has many constraints, trade-offs and compromises.

Orion PA-1 Phasing Test was conducted at White Sands Missile Range (WSMR) from March 4-6, 2010. This test decreased the risk of mission failure by demonstrating proper flight control system polarity. Demonstration was achieved by stimulating the primary navigation sensor, processing sensor data to commands and viewing propulsion response. PA-1 primary navigation sensor was a Space Integrated Inertial Navigation System (INS) and Global Positioning System (GPS) (SIGI) which has onboard processing, INS (3 accelerometers and 3 rate gyros) and no GPS receiver. SIGI data was processed by GN&C software into thrust magnitude and direction commands. The processing changes through three phases of powered flight: pitchover, downrange and reorientation. The primary inputs to GN&C are attitude position, attitude rates, angle of attack (AOA) and angle of sideslip (AOS). Pitch and yaw attitude and attitude rate responses were verified by using a flight spare SIGI mounted to a 2-axis rate table. AOA and AOS responses were verified by using a data recorded from SIGI movements on a robotic arm located at NASA Johnson Space Center. The data was consolidated and used in an open-loop data input to the SIGI. Propulsion was the Launch Abort System (LAS) Attitude Control Motor (ACM) which consisted of a solid motor with 8 nozzles. Each nozzle has active thrust control by varying throat area with a pintle. LAS ACM pintles are observable through optically transparent nozzle covers. SIGI movements on robot arm, SIGI rate table movements and LAS ACM pintle responses were video recorded as test artifacts for analysis and evaluation.

The PA-1 Phasing Test design was determined based on test performance requirements, operational restrictions and EGSE capabilities. This development progressed during different stages. For convenience these development stages are initial, working group, tiger team, Engineering Review Team (ERT) and final.

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<sup>1</sup> GN&C Analyst, Aerodynamics and Flight Mechanics, 2224 Bay Area Blvd./6W621, AIAA Member.

Many activities and meetings were held before the creation of the Tiger Team in October of 2008. There was no single scope that was agreed from all parties. There were two different groups that each had concepts. End-to-End was the goal of Avionics and Operations and Phasing Test was the goal of GN&C. These are dissimilar because the End-to-End test was a continuity test only that proved that all components are able to communicate once integrated. The Phasing Test was a higher fidelity test than the End-to-End which would verify that the communications from sensor to effector had the proper phase. The definition of a Phasing Test was provided at PA-1 PTR#2. The test was added to the GN&C Thread testing in Exploration Development Lab (EDL) and to the Mission Test Plan (MTP) for integration testing at WSMR. Meetings were held regarding the implementation of the test and have not determined or approved a clear forward path. Two specific meeting to develop these tests were on May 15, 2008, at NASA Dryden Flight Research Center (DFRC) to review capabilities and on July 1, 2008, at NASA Johnson Space Center with Orion Flight Test Office management to review issues.

The initial development was integrated into a single working group in October, 2008. This group was an interdisciplinary team consisting of participants from Guidance Navigation and Control (GN&C), Orion Launch Abort System Office (LASO), Flight Software (FSW), models and simulation, Integration and Test (I&T), operations and safety. Collaborative development was done for the EDL testing procedure and WSMR test definition. The team was by "Responsible Engineers" (REs) allocated from GN&C to the EDL testing organization. The initial goal was to provide more oversight to ensure the system has been adequately tested beyond the relatively shallow ground test-relevant GNC requirements for PA-1. These REs responsibilities and authorities included co-ownership of EDL procedure and script, signature authority on procedure, provides input and support for co-owned procedures and scripts (consults other SMEs as needed), attend all test runs, review test results and notify other GNC SMEs of test data availability. This effort created multiple design artifacts from concept development that was used during the following stage.

A Tiger Team was created on October 28, 2008 during a pre-ERT meeting held to agree on the test to be conducted. Many aspects of the test and the reasoning for the approach were requested as outputs of the team. This team had similar participation from the working group with added emphasis and stakeholder pressure to ensure participation. The team consisted of flight dynamics (GN&C), Orion Flight Test Office, Orion LAS Office, flight software, avionics, test and verification. A Tiger Team board was created as an intermediary level between the working-group level of the tiger team and the management level of each supporting organization. Buy-in from this board was required before any design was progressed to the management of each respective organization and the Engineering Review Team (ERT). This team initially functioned as a "Tiger Team" to facilitate rapid test definition and then converted to a working group to continue coordination for final development. This team quickly processed all the initial trade study materials and created multiple options to be presented to the Engineering Review Team for test design approval for development.

The team presented its results at the ERT held December 5, 2008. A smaller meeting was held with key members of the Phasing Board to determine options since the original recommendation was rejected. A reconvene of the ERT was held on December 16, 2008 to approve the new test design recommendation (Option 1). Option 2 created from sidebar discussion after first ERT meeting. Option 3 created after Option 2 was presented to the ERT.

ERT1 Test Configuration was defined to use SIGI with umbilical to Orion Crew Module (CM). SIGI moved by using Mobile Work Platform (MWP) like a JLG Man-Lift. With the Flight SIGI removed from the CM and placed on the MWP. Translate SIGI using MWP, rotate SIGI using gimbaled base (tilt table). FITF interior space for test is 80 foot long, 40 foot wide and 30 feet high. SIGI powered from portable power supply that is enabled through a toggle switch (no need to power from PDU). 1553 cable will be used (up

to 200 ft source to destination is maximum distance). Groundstrap tied from SIGI to MWP and from MWP to Ground. Personnel required: 1 driver of MWP, 1 operator of SIGI tilt table. Maximum rates of operation: horizontal translation at 2 to 3 ft/sec using wheels, 0.5 to 1.0 ft/sec using boom. Critical lift safety review needed for flight hardware. Prefer interior operation, accept limited range of motion. This design recommendation was rejected due to concerns over the MWP ability to recreate prescribed movements. There was concern over the safety of having flight critical hardware operated from an unusual platform.

Option 1 defined as moving the SIGI using a Mobile Work Platform (MWP) while rotating SIGI through different movement on a gimbaled mount. Option 2 defined as moving the SIGI in a controlled manner with robotic arm to record data and play back this data into the vehicle for tests (playback option). Option 3 defined as moving the SIGI with a rate table and using the robotic arm to record data for playback.

ERT approved Option 3, MRMDF Data Recording and Playback with Rate Table Motion Test, for use on Pad Abort 1 integration testing. The approved design uses a combination of a rate table and data recordings to cover all phases of flight. The use of soft-mate integration test configuration was used to perform the Phasing Test. Soft-mate connects the Launch Abort System (LAS) tower and the CM using umbilical harnesses. A rate table was used to move the SIGI to exercise the Pitchover Guidance algorithms in the Guidance, Navigation and Control (GN&C) Flight Software (FSW). A data recording was created by “flying” a SIGI with the Multi-use Remote Manipulator Development Facility (MRMDF) robotic arm to exercise the Downrange Guidance (DG) and Reorientation Guidance (RG) algorithms in the GN&C FSW.

The test design and lessons learned from Orion Pad Abort Test 1 were applied to the Orion Exploration Flight Test 1 (EFT-1) GN&C-Propulsion Phasing Test and GN&C-C&T Phasing Test. These tests progressed quickly through initial concept development based on the experience and results of PA-1 Phasing Test. These two tests will complete the primary GN&C end-to-end integration testing for EFT-1. Final test development continues and the final implementation of the design are to “anchor” the OIMU on a tilt table by recording data output from known inputs. These inputs will consist of sensed and test port data. The sensed data will come from Earth rotation and gravity. The test port data will be a series of rotation and acceleration inputs to the OIMU test port. All data output will be reviewed for validity of the OIMU and its electronic ground support equipment (EGSE). The tests on the flight vehicle for propulsion testing will be done using Earth-rate and open-loop simulation inserted on the test port of the OIMU. The tests on the flight vehicle for communications testing will be done using the open-loop simulation inserted on the test port of the OIMU.

## Nomenclature

A = amplitude of oscillation

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The preferred spelling of the word

## **References**

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